EFFECTS OF GLOVE AND LADDER RUNG DESIGN ON PREVENTION OF LADDER FALL

Pilwon Hur, Binal Motawar, and Na Jin Seo

Industrial and Manufacturing Engineering, University of Wisconsin-Milwaukee, Milwaukee, WI
E-mail: hur@uwm.edu, seon@uwm.edu Web: www4.uwm.edu/ceas/faculty_profiles/NaJinSeo.html

INTRODUCTION

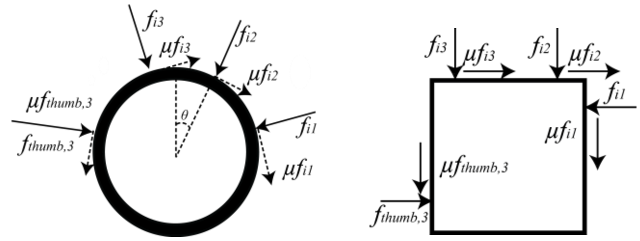
Falls from ladders are the leading cause of disabling falls to lower levels and the second leading cause of fatal falls to lower levels [1]. Hands are the only interface available to arrest the body once a fall has been initiated. Persons' physical capability to hold onto a ladder rung before the hand slips off the rung (i.e., breakaway strength) is not well understood. Conventional power grip strength is not an adequate measure of breakaway strength, since it considers only the finger flexion strength, not the frictional coupling between the hand and rung [2]. Improved understanding of the biomechanical coupling between the hand and rung is necessary to prevent falls from ladders and scaffolds.

Biomechanical models for breakaway strength for two representative rung cross-sections have been developed as shown in Fig. 1, based on our previous study [3]. The models assume that people apply the maximum possible shear force at each phalanx (= coefficient of friction, COF × phalanx normal force). The models suggest that breakaway strength is affected by the COF between the hand and rung, phalanx force distribution, and rung geometry.

The present study was undertaken to evaluate these biomechanical models by examining the effects of the COF at the hand-rung interface and rung shape on persons' breakaway strength (Experiment 1). In addition, to validate the model assumption that phalanx shear force increases with increased COF, the ratio of shear to normal force was examined for different COF conditions (Experiment 2).

METHODS

Thirteen right-handed healthy young adults (9 male and 4 female, age=25±5yrs) participated in this study. Subjects used their non-dominant hand for testing, because people typically use the dominant hand for main tasks (e.g., painting, reaching for something) while holding onto a ladder with the non-dominant hand.



Breakaway strength

$$= \sum_{i=1}^{4}\sum_{j=1}^{3} f_{ij}\left(\cos\theta_{ij} + \mu\sin\theta_{ij}\right) + f_{thumb,3}\left(\cos\theta_{thumb,3} - \mu\sin\theta_{thumb,3}\right)$$

Breakaway strength

$$= \sum_{i=1}^{4}\left(f_{i,3} + f_{i,2} + \mu f_{i,1}\right) + \mu f_{thumb,3}$$

Fig. 1 Biomechanical models of breakaway strength for two rung shapes. f_{ij} is normal force for *i*-th finger and *j*-th phalanx, μ is COF, and θ_{ij} is the angle between a vertical line and f_{ij}. Shear force can be up to COF × f_{ij}. Proximal, middle, and distal phalanges are *j*=1, 2, and 3, respectively.

For Experiment 1, subjects were seated and strapped down to a fixed chair, with their arm raised to grasp an aluminum rung. They were instructed to hold onto the rung as long as they could, while the rung was raised up at 7 cm/s (Fig. 2). The rung was attached to a pulley whose chain was connected to a winch on one end (to raise the rung) and to a fixed load cell on the other end (to record hand force at 1 kHz). Breakaway strength was determined as the highest hand force recorded (typically occurred immediately before the subject lost the grip of the rung). Three COF conditions simulated by different gloves (COF of 0.33 for a polyester glove, 0.57 for the bare hand, and 1.11 for a latex glove against the aluminum rung) and two rung shapes (a circular cylinder with a radius of 25

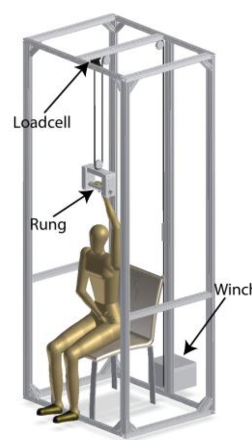


Fig. 2 Experimental setup

mm and a square bar with 38 mm×38 mm cross-section) were tested.

Fig. 3 Custom-made circular dynamometer

For Experiment 2, subjects performed an isometric pull exertion on a custom-made dynamometer mimicking the circular rung (Fig. 3) using the same posture and holding strategy as in Experiment 1 for 5 seconds, while normal and shear forces for each phalanx of a finger were recorded [4]. Testing was repeated for five fingers and three COF conditions in a randomized order. The ratio of shear force to normal force was computed for each phalanx, finger, and COF condition. Subjects were instructed to apply 50% of their perceived breakaway strength to reduce muscle fatigue and to allow accurate force recording for each phalanx without finger moving across the three measuring contact pads (Fig. 3).

For Experiment 1, repeated measures analysis of variance (ANOVA) was performed to determine the main and interaction effects of the COF and rung shape on breakaway strength. For Experiment 2, another repeated measures ANOVA was performed to determine whether the ratio of shear force to normal force significantly varied with COF, fingers and phalanx where fingers and phalanx were blocking factors. The level of significance was α=.05 for both tests (SPSS Inc., Chicago, IL; v17). *Post-hoc* tests were performed to evaluate differences among the three COF conditions.

RESULTS

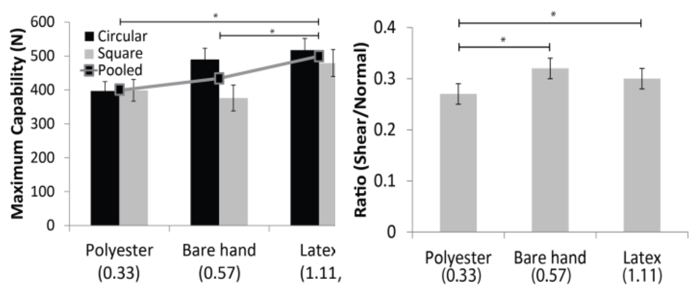
The breakaway strength significantly varied for COF, rung shape, and their interaction (p<.001, Fig. 4a). Increased COF was associated with increased breakaway strength (Fig. 4a). The circular rung resulted in, on average, 12% greater breakaway strength than the square rung (Fig. 4a). The ratio of phalanx shear to normal force significantly varied for COF (p=.01, Fig. 4b). The two high COF conditions (bare hand and latex) resulted in a significantly greater ratio than the lowest COF condition (polyester glove).

DISCUSSION

The biomechanical models in Fig. 1 are generally supported by empirical results. Breakaway strength increased with increased hand-rung COF, as can be predicted by the models (Fig. 1). The models also predict that breakaway strength can be, on average, 7% greater for the circular rung than for the square rung across the three COF conditions, using the phalanx normal forces from Experiment 2 and finger dimensions [5]. This prediction is also consistent with the empirical results (Fig. 4a).

Subjects modulated the phalanx shear to normal force ratio depending on the COF condition. An increased shear to normal force ratio with increased COF may indicate that subjects utilize frictional coupling within available COF to increase breakaway strength. The extent of increase in the ratio with increased COF was less than expected, possibly due to the Experiment 2 task of 50% isometric pull exertion rather than maximum. The greatest mean shear to normal force ratio for the bare hand followed by the latex glove may be related to the bare hand's being most sensitive in detecting COF and the latex glove having the thickest layer hindering detection of COF for submaximum pull [6].

Design of handles and rungs should account for the COF and shape to increase persons' breakaway strength. Optimal design may help prevent future falls from ladders/scaffolds and associated fatalities.



(a) (b)

Fig. 4 (a) Breakaway strength for the three COF and rung shapes. (b) The mean ratio of shear to normal force on the phalanges during 50% pull (* shows p<.05)

REFERENCES

1. BLS, *Census of Fatal Occupational Injuries*, 2009
2. Young JG et al. *Human Factors* 51:5, 705-717, 2009
3. Seo NJ et al. *Ergonomics* 53:1, 92-101, 2010
4. Enders LR et al. *JBiomech*, In Press, 2011
5. Wickens CD et al, *Pearson Prentice Hall*, 2004
6. Kinoshita, *Ergonomics* 42:10, 1372-1385, 1999

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